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The Visible Nulling Coronagraph-- Architecture Definition and Technology Development Status

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(representing the work of many)

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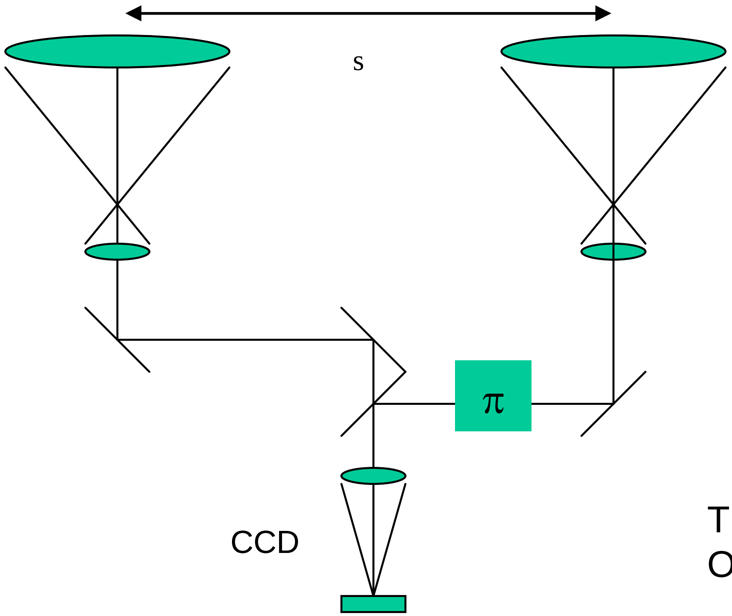
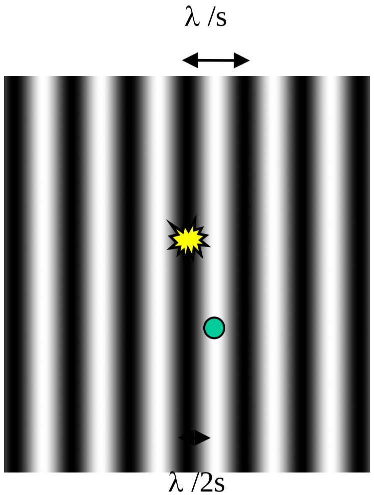
Overview

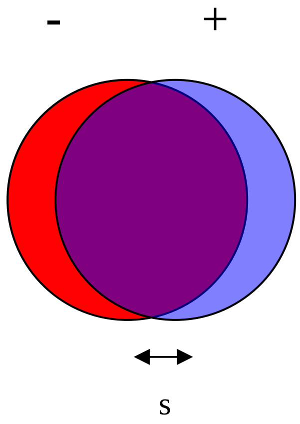
- Concept (advantages)
  - Science
  - Instrument/operations
    - Summary of thurs even talk
- Experimental results (technology) how we do it
  - Deepest Laser null 1.2x10-10/airy spot
  - Deepest whitelight null 1.5x10-9/airy spot
  - Future full imaging experiment
- Planned missions using this technology
  - Picture (sounding rocket, 1st hyper coronagraph in space)
  - Gemini Planet Imager (LLNL, AMNH, HIA, JPL etc.)
  - TMT Planet finder
  - EPIC VNI coronagraph (discovery proposal)

Planet Detection with a Nulling Interferometer





Transmission Pattern of Nuller
On the sky. (Star is at the center)



- **When the light from two pupils are combined, the output can be imaged.**
  - The image is an Airy function with diameter 2.44l/D where D is the telescope diameter.
- **But the intensity of that image is modulated by the fringe pattern (on the sky) where b is the baseline between the pupils.**
  - If the star is at a null, the star’s image has 0 intensity. If the planet is at the peak, the planet’s light is unattenuated.
- **A nulling interferometer that works with a single aperture telescope is different than one that combines light from 2 or more telescopes**
  - For an Earth @ 10pc 2s~1.5m
  - **This type of interferometer is synthesized by shearing the telescope pupil**

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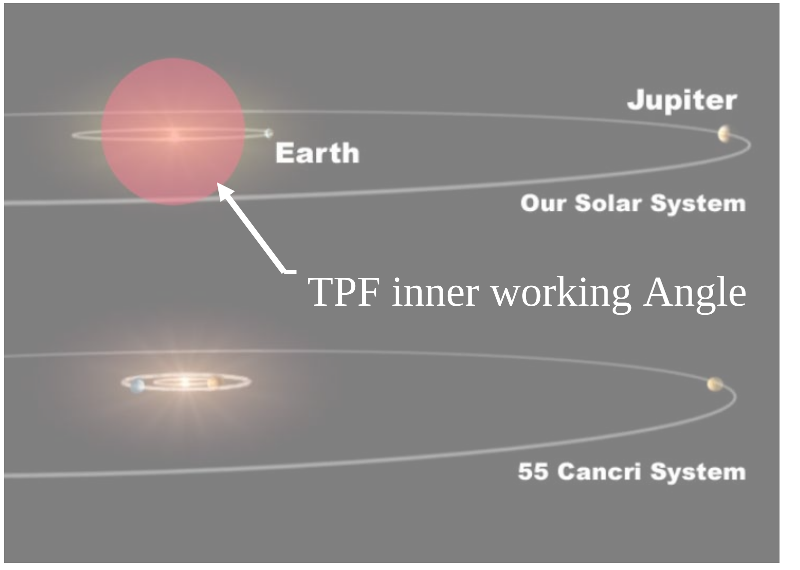
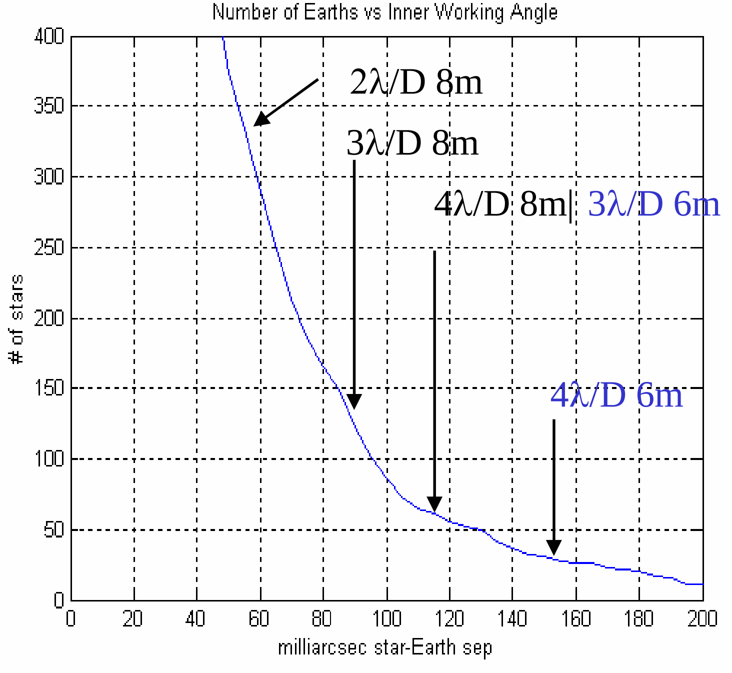
Inner Working Angle, Key to Exo-Earth Detection

- The IWA, inner working angle is the angle inside which direct detection of a planet is not possible. (N*λ/D)
- Different types of coronagraphs have IWA with different values of N
- Next to Contrast, IWD is a driving requirement

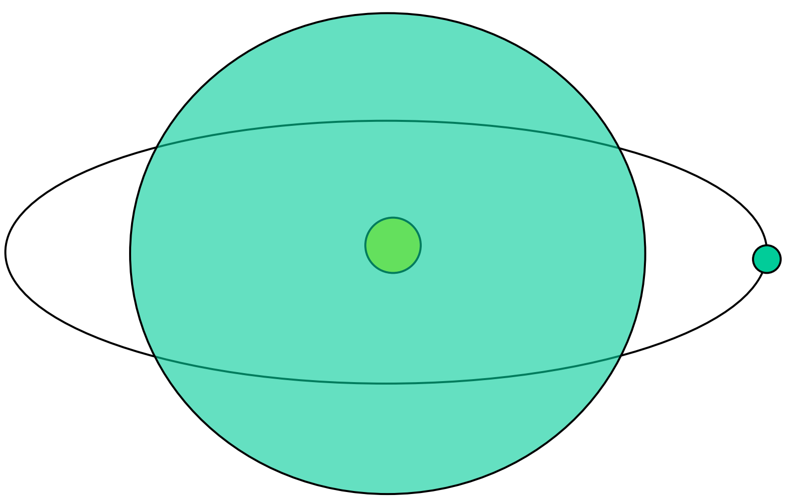




- The smaller the IWA, the greater the number of stars available for search in the habitable zone.
  - Late F,G,K, and M main sequence dwarfs
  - Habitable Zone @ 300K

Science Importance of Small IWA/0.9~1.6um

- Near IR spectra of TPF targets can not be obtained without working at < 4 λ/D. Strong Methane features, an O_2 line, stronge H_2O and CO_2 features
- A much larger target list in the visible.
  - One can estimate the minimum mass planet detectable by TPF-C by looking at each nearby star and putting a terrestrial planet (0.5~10 Mearth) in the mid HZ and adjusting the mass until the contrast is just better than 1e-10.



IWA inner working angle

Mid HZ (1AU for 1 solar Lum star)
Max star planet sep > 58 mas (IWA)
Planet/star contrast = 1.15e-10 for a 1 Earth planet @1 AU (90deg phase)
Constrast scales as R_{planet}^2 or M_{planet}^(2/3)

<u>Min detect mass is => contrast = 10^{-10}</u>

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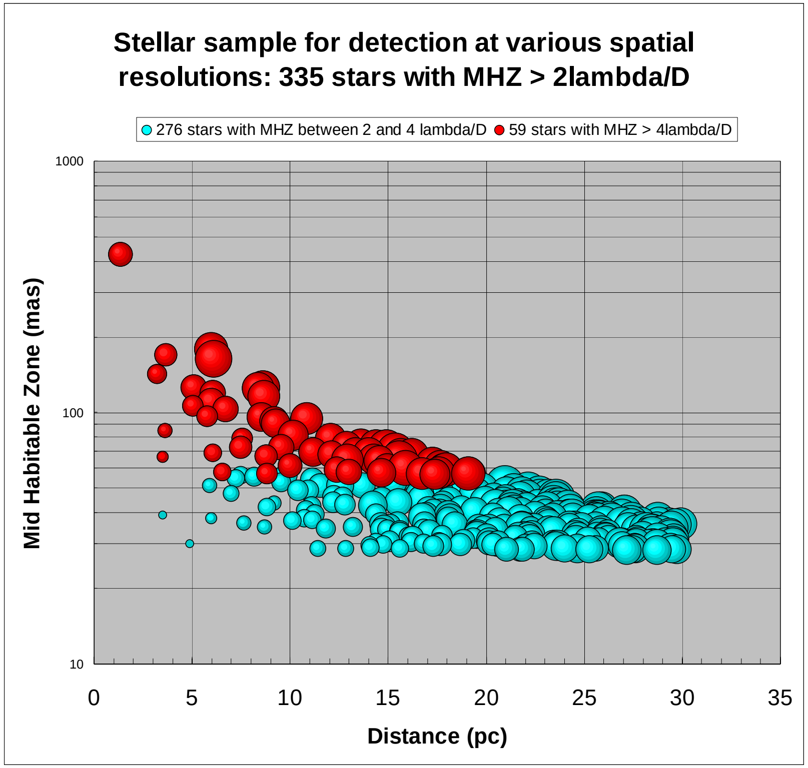
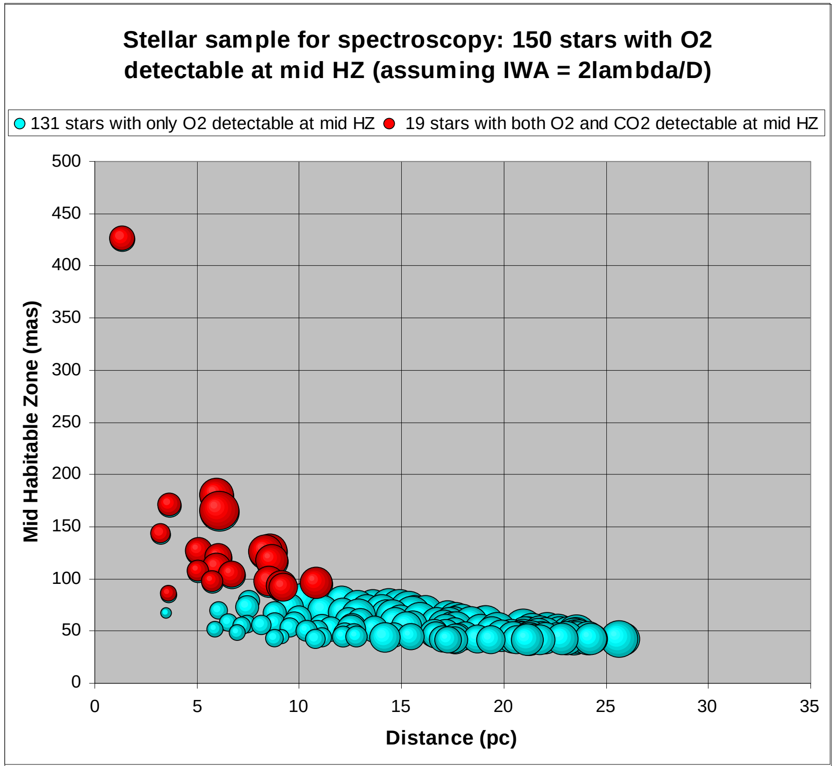
Science Implications of 2 λ/D IWA

- The number of potential targets in a search for Earths is significantly enhanced with a smaller IWA.
  - Number of potential targets greater by ~5X





- For detection of Oxygen O_2
  - # potential targets > ~7X

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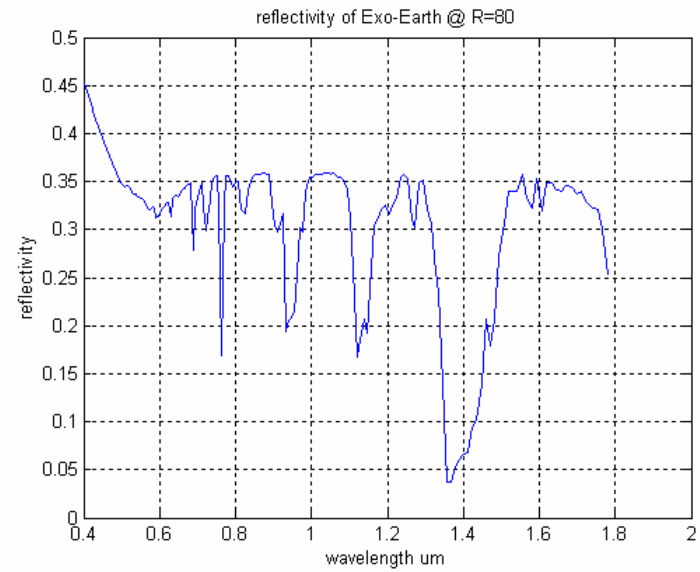
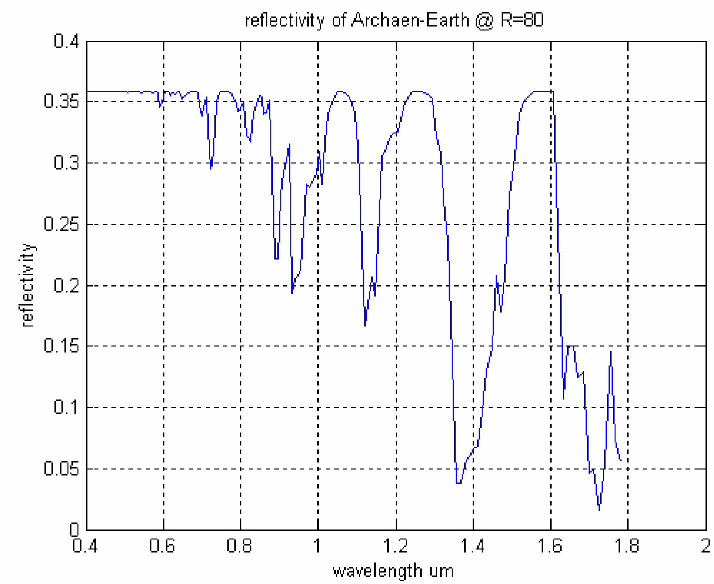
Near IR Spectroscopy of Exo-Earths

- The 0.5um~0.8um band was designed for a “modern” Earth.
- CO_2, CH_4, H_2O all have strong features in the near IR, feature that may let us distinguish a modern Earth and an Earth before it had an oxygen rich atmosphere

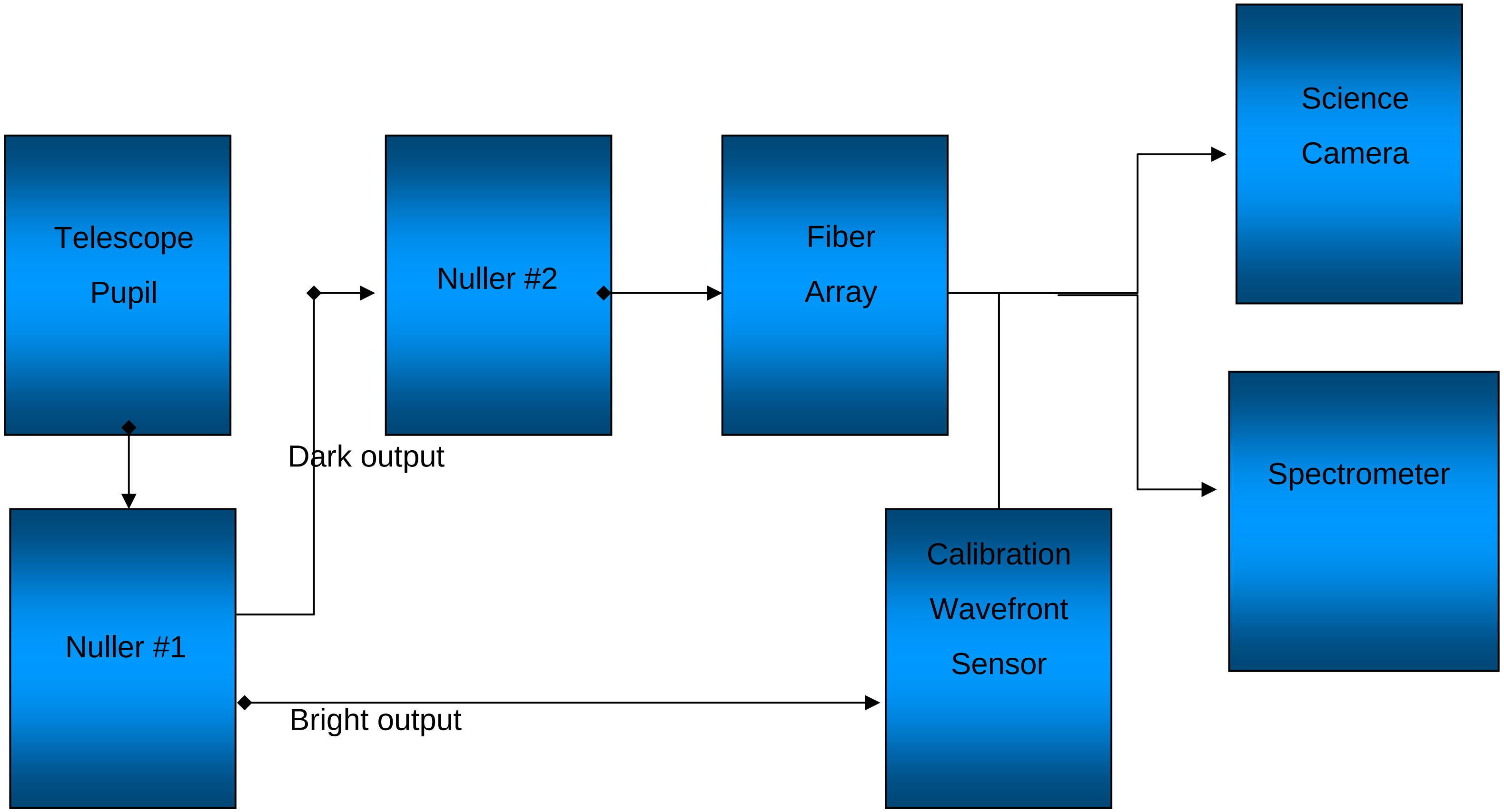
- Near IR spectroscopy is also very important for the study of exo_jovian/neptune planets.





# potential targets versus wavelength			
	Detect Earth	Det Oxygen	NIR
wavelength	(0.5~0.6um)	0.78um	1.6um
2 λ/D	276	131	20
4 λ/D	59	19	3

Nuller Architecture for Planet Imaging

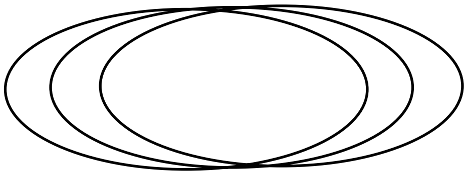


Calib wavefront sensor has 2 functions

1) Measure the post coronagraph WF and supply data to DM
2) The measured wavefront is used to estimate the residual PSF for subtraction in software (to ~3%)

4^{th} Order Null 8*3.5m Aperture

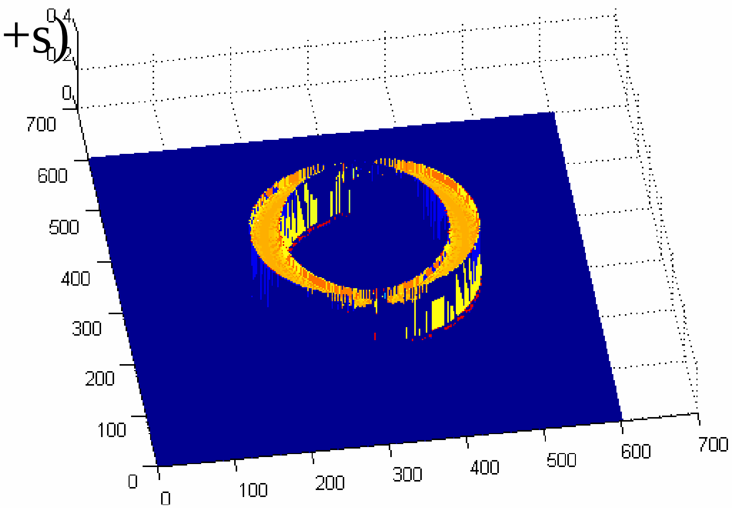
- Dual nuller with two identical X shears
- Produces a θ^4 null
- Properties of Nuller
  - Lyot efficiency



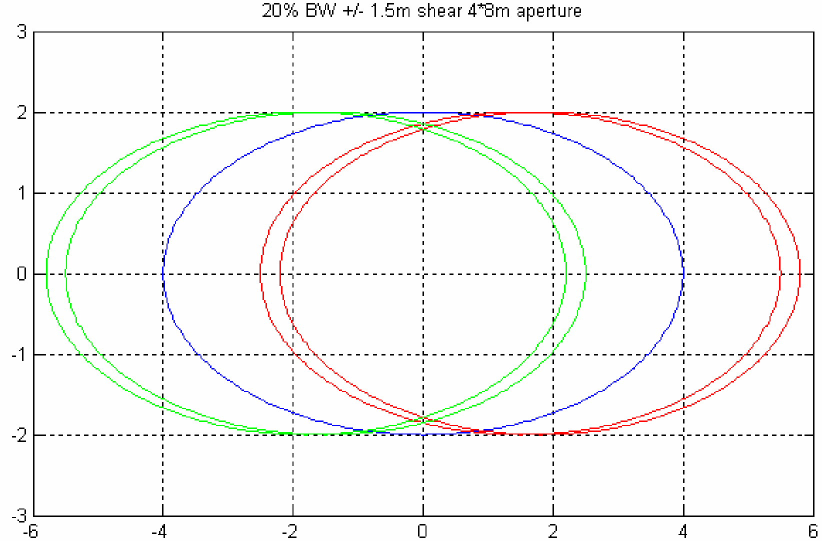
Amplitude split
-0.25, +0.5, -0.25

Lyot Efficiency (Broadband)

- A nulling coronagraph has a band limited lyot coronagraph counterpart, that in monochromatic light has the same properties.
- Sum of 3 sheared pupils -0.5*(-s), 1*(0), -0.5*(+s)
- In a nulling interferometer, the shear is set by the location of the optics. In a lyot coronagraph the shear is proportional to wavelength. (because the shear is generated by a sine^2 wave in the image plane mask)
- With a 20% bandpass the shear will change 20%.



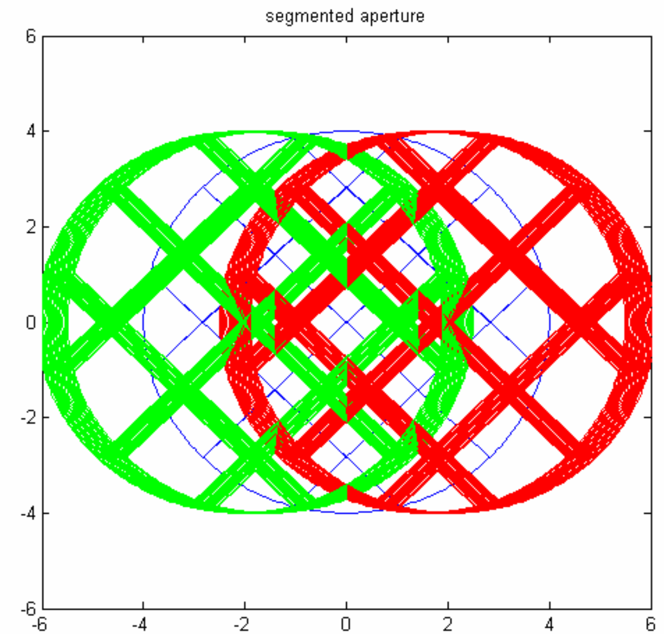
20% BW +/- 1.5m shear 4*8m aperture

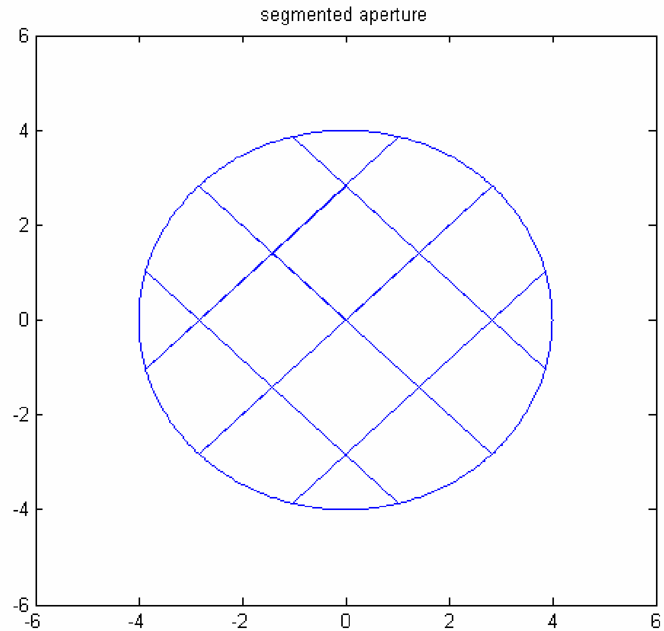


@ 2 l/D, the shear is ~4m the lyot advantage of a nulling interferometer over its lyot equivalent is ~20%

Telescopes with Obscurations

- The efficiency advantage of a nulling interferometer at the lyot stop is greatest for a telescope with obscurations, to the point where it makes the difference between a coronagraph that works or doesn't work.

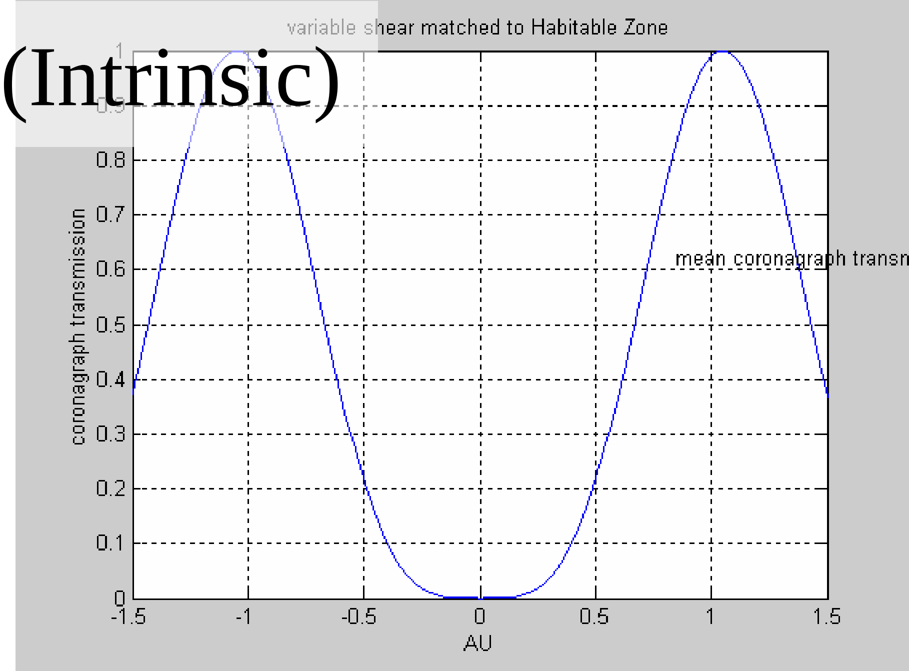




Nulling interferometers are much more tolerant of aperture obscurations. The internal obscurations are only copied twice for the nuller.

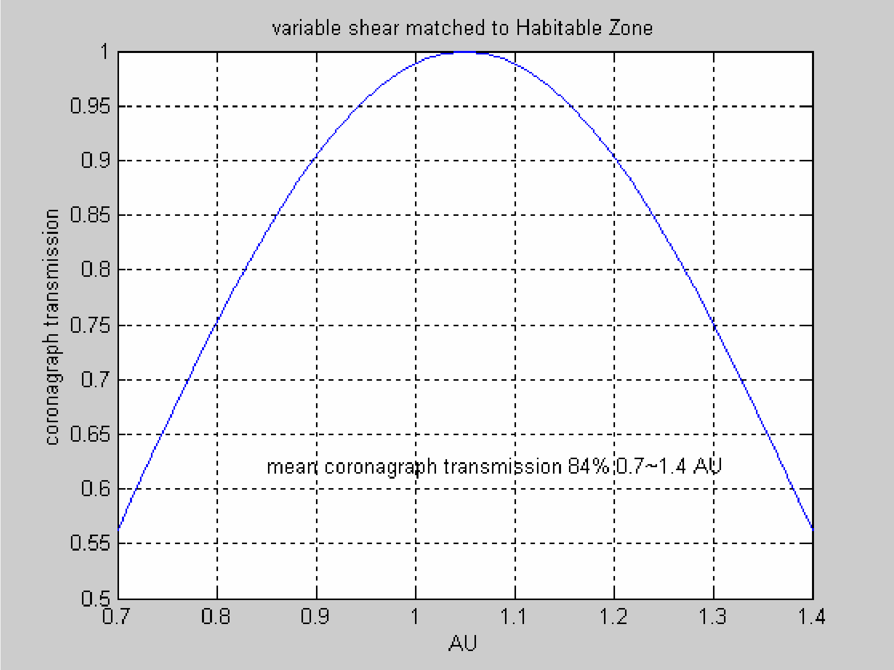
For large aperture telescopes, there can be major cost advantages to using on-axis optics, and segmented primaries. In a changing political environment, this could become a decisive advantage.

Throughput (Intrinsic)



- Nulling Coronagraph (perhaps like other concepts) is tuned to the target.
- Shear is set to provide the best coverage of the Habitable zone, for each target star.
  - Null transmission **84%** average over HZ
- Lyot efficiency depends on what IWA is set for (For an IWA of 62 mas, Lyot efficiency is **77%)**
- Equiv to baseline TPF-C total throughput (avg over HZ) is **65%**

IWA	Lyot	Total
4 λ/D	77%	65%
3 λ/D	70%	59%
2 λ/D	55%	46%



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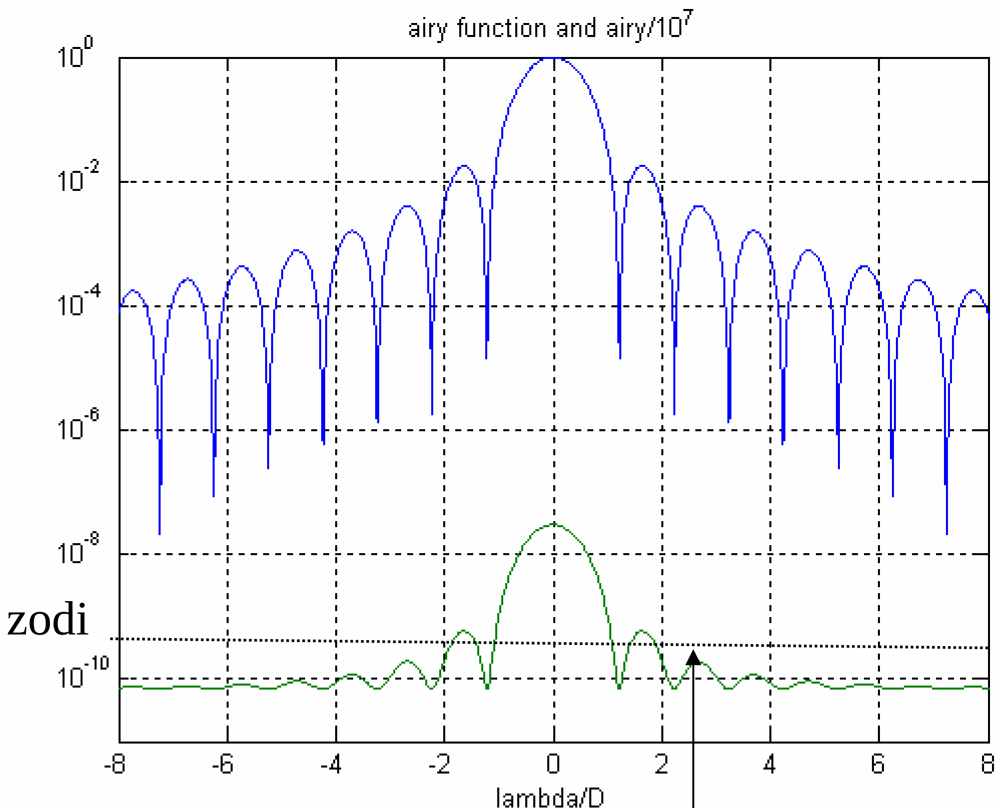
Depth of Dark Hole vs Starlight Suppression

- **10^{-10} scattered light level** implies ~**10^{-7} suppression** of starlight



2×10^{-10} lower than zodi peak measured and subtracted by PSF subtraction

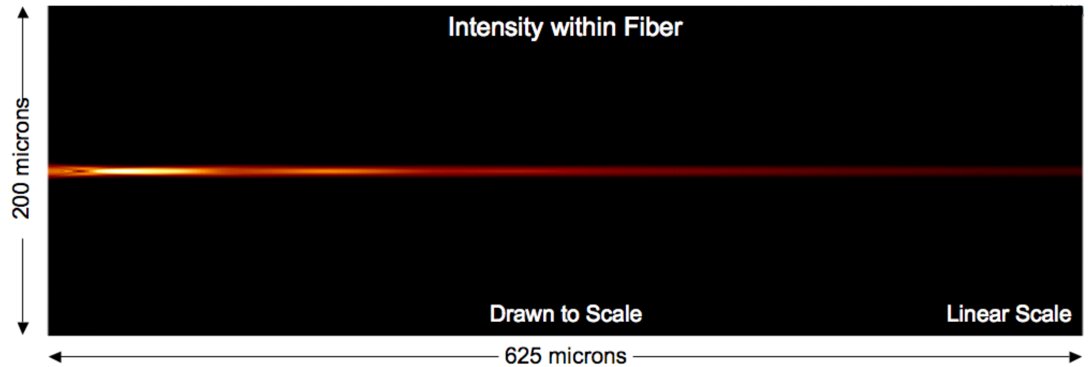
Error budget allocation

OPD err	4e-8
Amplitude	3e-8
Polarization & color	3e-8

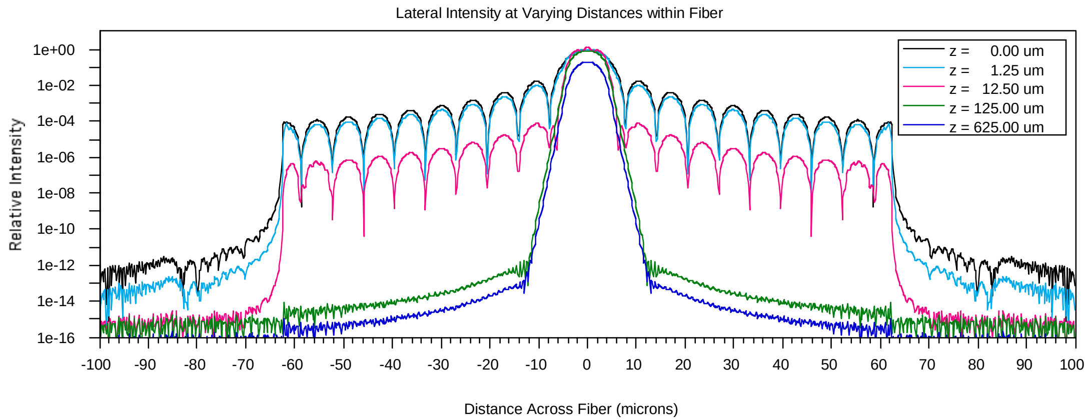
Blue – Controlled per sub aperture residual light residue scattered over fov.

With post coronagraph wfs, the bump @3 λ/D is measured and subtracted, noise is dominated by local/exo-zodi. Letting the nuller work to ~2 λ/D

Modeling/Analysis of Fibers

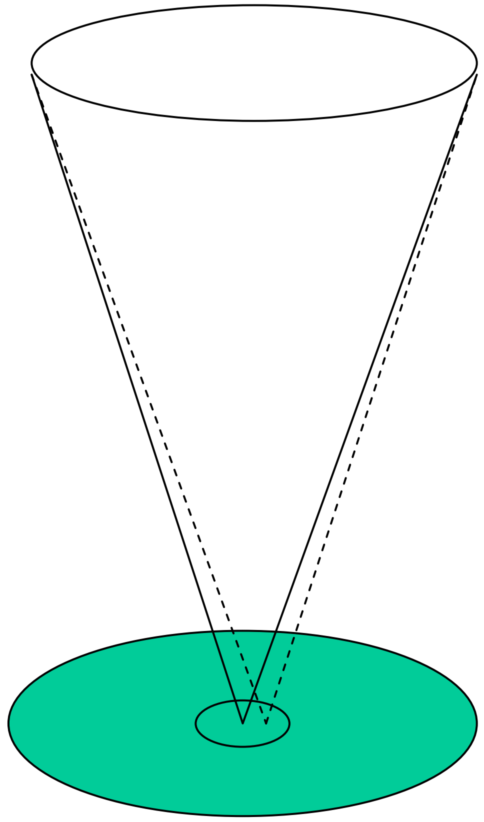


- R. Lyon has done extensive modeling of what happens to the light in single mode fibers, how far down the fiber does the light have to get before it's single mode?



Amplitude Control (Chromatic Effects)

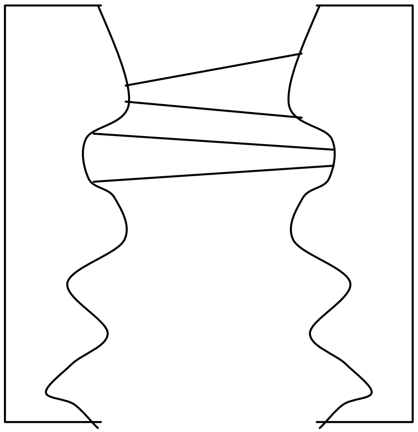
- Our baseline approach to amplitude is to tilt the beam to change the coupling of the light into the fiber.
- The diff limited image of the sub aperture is λ dependent. A given tilt will produce a larger amplitude change at shorter λ.
  - We've known this for some time.
  - A more detailed analysis by Palacios and Shaklan shows that this λ dependence is identical to the 2DM michelson
- Roughly speaking, correcting a 0.5% amplitude mismatch to 0.05% can be done only over a bandwidth of +/-10% or less.
- This puts a limit on the size of amplitude errors due to both reflectivity and phase induced amplitude errors that this approach can accommodate.



Achromatic Amplitude Correction by PIAA

- The baseline approach for amplitude correction for the Visible nuller had been to offset the the image of the star on the array of single mode optical fibers.
- An alternative (more achromatic) approach is to use the PIAA effect (Guyon). Also suggested for TPF-C/coronagraph by Shaklan.

Curvature in 1st optic causes both amplitude and phase effects at 2nd optic which removes the phase errors.



Two implementation approaches

2 DM's

1 Fixed optic (to correct amplitude to < 0.5% p-v) and 1 DM to correct the phase errors of the fixed optic AND all other OPD errors

Wavefront Stability

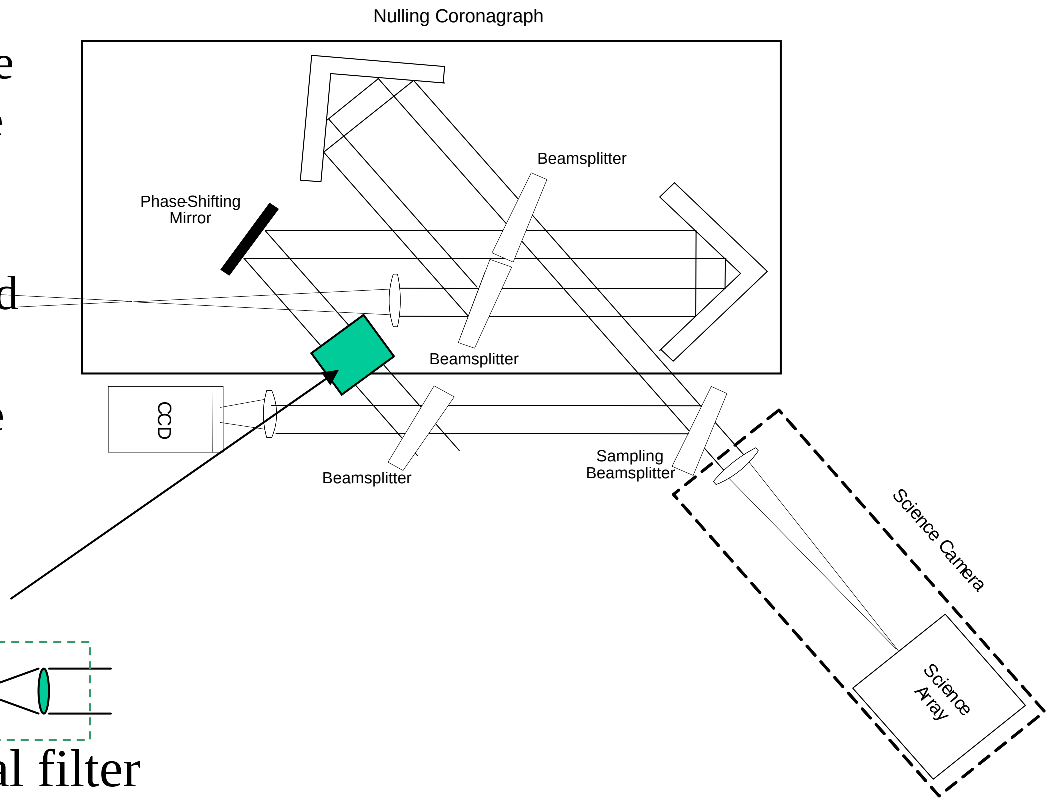
- A 10^{-10} speckle pattern has to be subtracted to ~ ~2×10^{-11} for a 5 sigma detection of a planet @ 10^{-10}. The speckle pattern has to be measured with ~ 10^{-11} precision.
  - TPF-C baseline approach uses an 8th order mask to reduce sensitivity to changes in low order abberations. Expected changes in focus, decenter etc produce primarily changes in low order wavefront errors. At the expense of throughput of the 8th order lyot mask.
  - The Nuller/PCWS concept is the equiv of a 4th order mask, but reduces sensitivity (to changes in the speckle pattern at 10^{-11} level) by measuring the post coronagraph wavefront. By doing this **simultaneously** with the collection of data, the stability requirement is reduced from a few hrs to a fraction of a second. This reduction is so large >1000X that 10^{-11} stability of the speckle pattern is no longer the driving factor. (stability for servo operation is).
- This reduction in stability applies to < 1hz thermal drift.

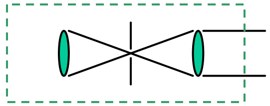
PSF Calibration: Separating the Starlight Speckles from the Planets

- **A high contrast imaging system for extra-solar planet detection requires PSF calibration to combat the effects of post starlight suppression errors**
  - How can you tell the difference between starlight speckles and planet light?
  - By using the coherence of starlight and property that the star light and planet light are incoherent with each other.

•Stuart Shaklan said yesterday, the baseline TPF-C approach is to require the wavefront (esp low zernikes) to be stable to single digit pm for many hours (using telescope rotation for PSF subtraction)

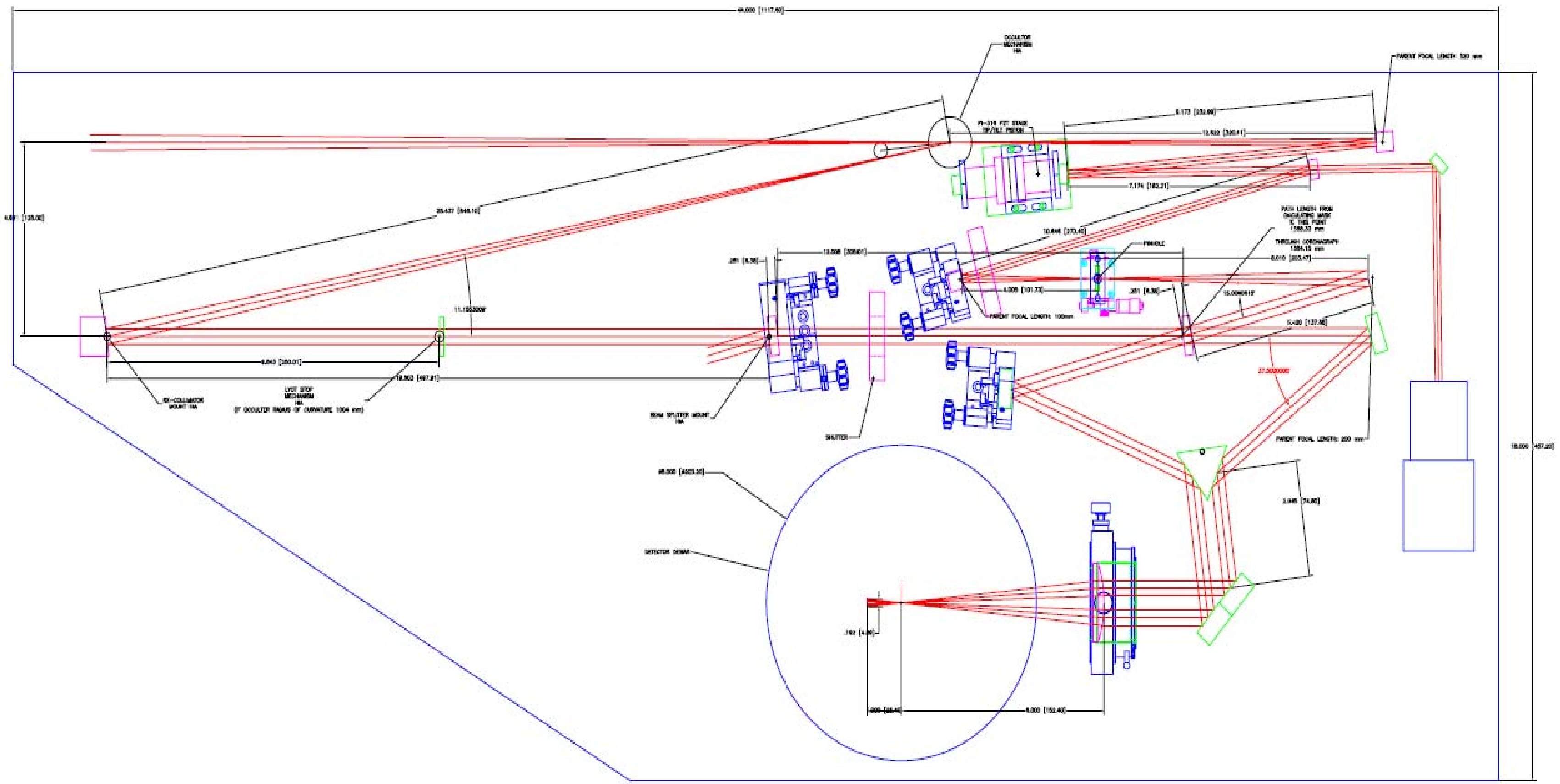
•**This requirement pm/hr** can be relaxed by **many orders of magnitude** if the PSF is measured simultaneously with the science image. (instead of 5hrs later)





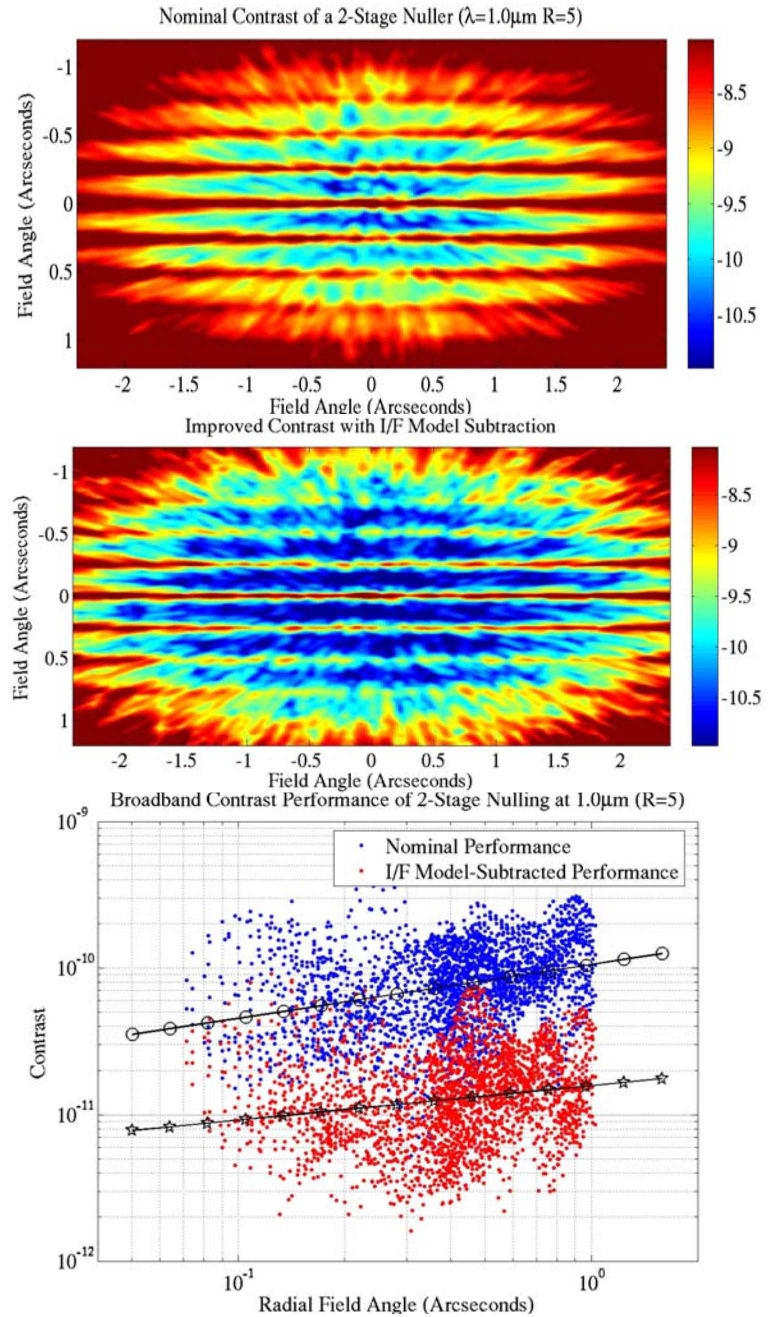
Spatial filter

Layout of the GPI Calibration System

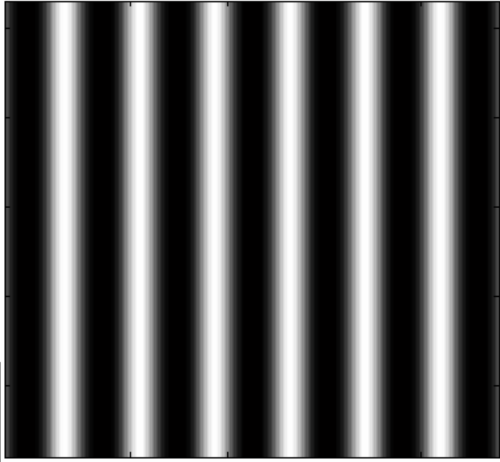


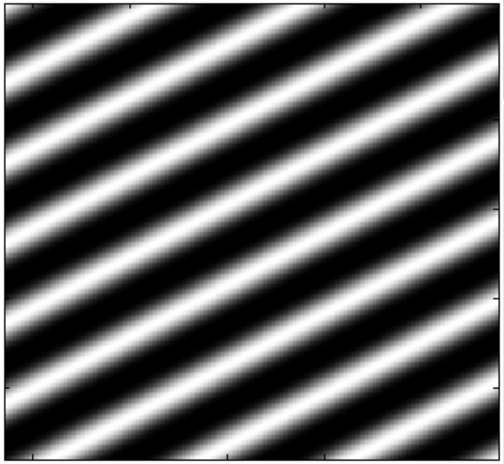
Post Starlight suppression wavefront sensing

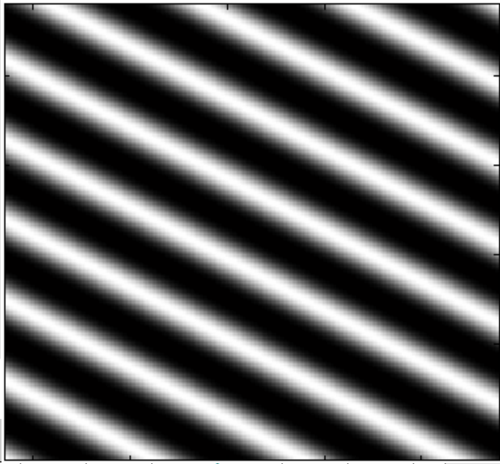
- θ^4 nuller
- Shot noise, Detector noise, pixelization included
- Principle limitation of this post Coronagraph wavefront sensor/PSF estimator is chromatic errors.
- Contrast improvement factor of ~30X



Operational Sequence

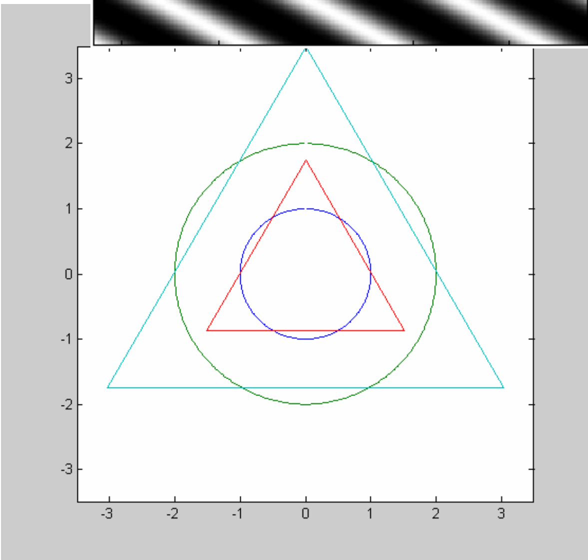






- 1st rotation
  - Linear θ^4 null, width is transmissive band = width of habitable zone.
  - Simultaneously make science and WFS exposures. Update DM at optimal rate (determined by wavefront stability and photon noise)

- 3 rotations (0 deg, +/- 60 deg)
  - Similar to baseline TPF-C design



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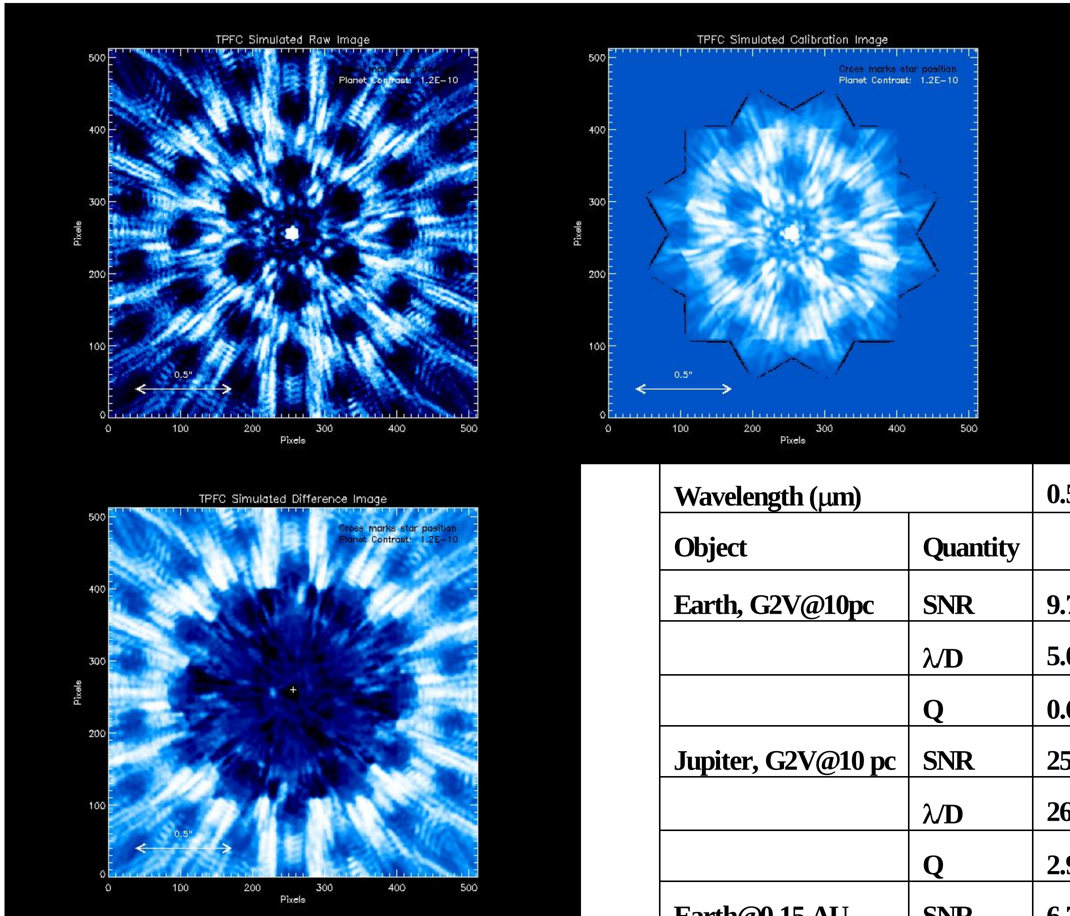
Operation

Raw image
3 rotations



PSF estimate from PCWS

PSF subtracted image

Wavelength (μm)		0.55	1.00	1.50
Object	Quantity			
Earth, G2V@10pc	SNR	9.76	9.81	5.34
	λ/D	5.06	2.45	1.42
	Q	0.68	0.52	0.19
Jupiter, G2V@10 pc	SNR	25.51	28.79	20.81
	λ/D	26.39	12.65	7.05
	Q	2.90	3.70	1.95
Earth@0.15 AU	SNR	6.79	3.17	1.16
M2V@5pc	λ/D	1.22	0.54	0.26
	Q	0.41	0.03	0.01

•Simulated image of an Earth-like planet at 10pc taken through the 8x3.5m aperture TPF telescope.

•Top left, raw image after 3 1hour exposures taken 120degrees apart.

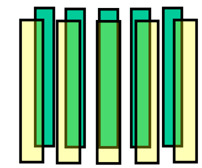
•Top right, estimate of leaked starlight psf.

•Bottom left, psf subtracted image.

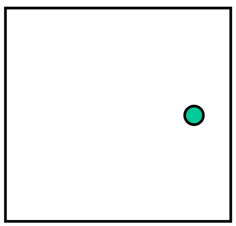
•Sensitivity summary for selected star-planet systems. All cases assume a 1 hour integration time and 20% bandpass.

Wavefront Sensing SNR (summary)

- The post coronagraph wavefront sensor uses pupil plane wavefront sensing
  - Image plane wavefront sensing is inherently chromatic
- In the past, we've grown accustom to needing many hours (~10hrs) to measure the wavefront using a thermal white light source. (<10 nwatts)
- Our wavefront sensing approach can measure the wavefront (to 1e-9/airy spot) **not in hours** of integration but in **100 millisec**.
- In space TPF-C looking at 10nw of light **HAS** to measure the wavefront in < 1 sec. (If there's any hope of searching for planets around 7 mag stars.



One spot in the image plane respresents one spatial freq in the pupil, at ONE wavelength



In white light one pixel represents many spatial freqs.

Modeling

- The purpose of modeling is to gain understanding of the physics of extreme starlight suppression. With understanding hopefully, will come a design (or variants of a design) that can suppress starlight by 10^7 for 10^{-10}/airy spot residual scattered light.
- Two approaches (of many)
  – Pick a complex system and apply a complex physics based end to end model.
  – Pick a very simple system (simple in terms of the physics we need to model to get to 10^{-11}/airy spot)
- That's why we went with single mode fibers. (similar to TPF-I)
- **<u>Within the core of a single mode fiber</u>**
  – There E_field amplitude and phase (both fn of λ) in 2 polarizations, and **<u>nothing else</u>**
- This simple model accounts for all of the physics down to 10^{-11}/airy spot.
  – Many effects (error sources) in lyot coronagraphs don't exist is systems that use single mode fibers (eg beating of high spatial freq errors into the dark hole, or polarization issues in um scale binary masks)

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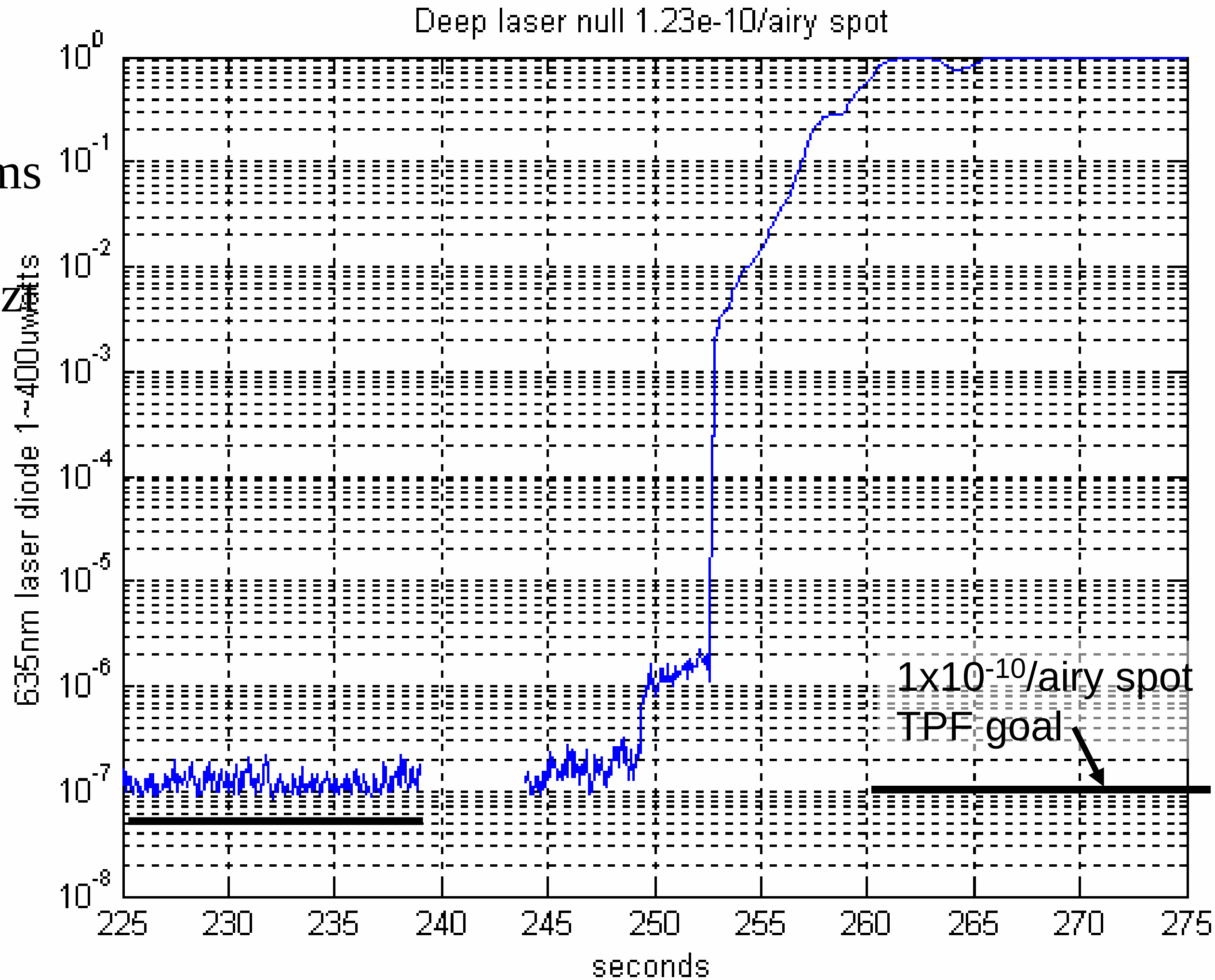
The Accuracy of Our Models is Demonstrated by Our Data

- **1.23×10^{-10}**/airy spot laser null
- Quiet environment, rms opd vibration <60pm. As well as very low pzt creep in our actuator.



The bottom of the nulls are slightly below 1×10^{-10}/airy spot if our setup was as stable as the HCIT vac chamber, it's likely this null would be below 1×10^{-10}/airy spot